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Sizing and Simulation of a Piston-prop UAV

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Abstract

A sizing and simulation platform has been developed for the optimization of advanced configurations for aircrafts including, but not limited to, more electric, hybrid-electric, turbo-compound piston engines and fuel cell systems. In the present investigation the software has been applied to the simulation of a medium-altitude, medium-endurance unmanned aerial vehicle (UAV) equipped with a two-stroke diesel engine with a single stage turbo-compressor. The engine was simulated with a 1D code (AVL-Boost) taking into account several values of speed, air-fuel ratio and flight altitude. The behavior of the waste-gate valve at the different flight levels was also accounted for. The Willans line method is used to obtain the seal level and in flight performance map of scaled engines with the same configuration. The power requests of a reference 128kW engine and two scaled engines along the mission have been compared with the available power to discuss the potentiality of hybrid electric and turbo-compound configurations.

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Keywords: diesel engine; aircraft; 1D modeling; performance maps

1. Introduction

The need of reducing greenhouse and pollutant emissions from aircraft has led to the investigation of advanced propulsion systems like hybrid electric systems [1]. Hybrid electric systems allow the improvement of engine operating points by avoiding idle and part load conditions. Moreover, it is possible to downsize the engine thanks to the additional power provided by an electric machine and use electric driven auxiliaries instead of inefficient hydraulic actuators. Finally, the airplane can be flight in electric mode thus reducing the acoustic, smoke and thermal signature, interferences between exhaust gases and chemical-detecting sensors [1], [2] and local emissions. On the other hand, hybrid systems have the disadvantages of higher complexity, cost, weight and volume of the powertrain, principally because of the batteries. In other advanced powertrains, the engine itself can be used to generate electric or mechanical power though the use of turbo-compound systems [3].

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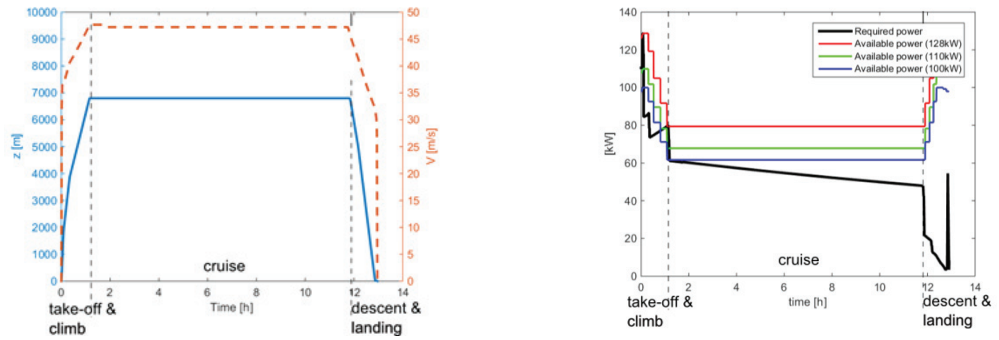
The present investigation focuses on the possibility of optimizing the working points of a two-stroke diesel engine in a medium-endurance unmanned aerial vehicle (UAV). The working points were calculated with the aircraft simulation software PLA.N.E.S [3] that uses a backward simulation approach to assess the performance and the consumption of conventional and advanced configurations over a pre-assigned mission. In this way, the benefits of adopting advanced electric solutions can be evaluated over the entire flight. PLA.N.E.S includes a design workflow for the input of aircraft specification and configuration (more electric, hybrid electric, turbo-compound, etc.) and for the definition of each component. The powertrain components, that are simulated with performance maps, include energy converter (piston engine, turboprop, turbojet, fuel cell, etc.), energy storage system (batteries, super-capacitors), auxiliaries and secondary power systems. It is also possible to setup different energy management strategies for the optimal control of the energy flows among engine, secondary equipment and storage systems during the mission.

2. The aircraft model

The UAV considered in the present investigation has a wing span of 9.94m, a wing area of 10.8 m^2 and a takeoff mass of 1080kg. The power electric auxiliaries during the different flight phases were assumed from [5] to be 3,8 and 5kW at takeoff/landing, cruise and climb/descent, respectively. The mission profile (speed V and altitude z) of Fig. 1a was considered in the present investigation.



a) b)

Fig. 1. Mission analysis (a) speed V and altitude z versus time; (b) Time history of required and available power

The equilibrium of the forces acting on the airplane in any phase of flight can be written in the lift (L) and drag (D) directions as:

$$L = W\cos\gamma - m\ V\ \frac{d\gamma}{dt} = \frac{1}{2}c_L\rho V^2 \tag{1}$$

$$T = D + W\sin\gamma + m\ \frac{dV}{dt} + \mu W = \frac{1}{2}c_L\rho V^2 + W\sin\gamma + m\ \frac{dV}{dt} + \mu W \tag{2}$$

Where W and m are the instantaneous weight and mass of the aircraft, respectively, c_L is the lift coefficient, γ is the climb angle. The rolling force μW is zero in flight while the gravitational force W is zero at land. The rolling coefficient is assumed to be 0.025 at take-off and 0.35 in braking.

The drag coefficient at take-off and landing is assumed from literature values while in flight it is:

$$c_D = c_{D0} + \frac{1}{\pi AR\ e} c_L^{\ 2} \tag{3}$$

Where *AR* is the aspect ratio of the aircraft (9.16) and *e* is the Oswald's efficiency (0.8). Cd_0 is assumed to be 0.018.

In the backward approach used in PLA.N.E.S., at any time-step the lift force (and the corresponding lift coefficient) is calculated from (1). Then, the drag coefficient is obtained (3) and the thrust requested at that time step is calculated by using equation (2). The instantaneous values of thrust and speed are used to enter the efficiency map of the propeller and to calculate its efficiency η_p.

In the present investigation, a conventional piston prop engine is considered. The propeller is assumed to be run at constant speed so the engine speed is also constant and related to the propeller speed from the gear transmission ratio. Assuming that the electric power for auxiliaries P_{aux} is produced by the engine through a generator with constant efficiency η_g, the total power P_{ICE} to be produced by the engine is:

$$P_{ICE} = \frac{T \cdot V}{\eta_P} + \frac{P_{aux}}{\eta_g} \tag{4}$$

Along the mission of Fig. 1a the maximum engine power request is at take-off and corresponds to 128kW (see Fig 1b). This value was used to size the reference engine and model its behavior. Note that at any time step the aircraft mass is updated according to the fuel consumption calculated in the previous time step so it is reduced by about 20% at the end of the mission. This also explains the reduction of power request from the beginning to the end of the cruise phase in Fig. 1b.

3. The engine model

A two-stroke diesel engine with 3 cylinders, a total displacement of 2.8liter and a squared configuration has been considered and modeled with AVL Boost [6] . A turbo-compressor, driven by the turbine, delivers the compressed air to an after-cooler and then in the plenum. After this element, air enters the three cylinders through the inlet ports. After combustion process, exhaust gases are discharged in exhaust duct and then they flow into turbine inlet.

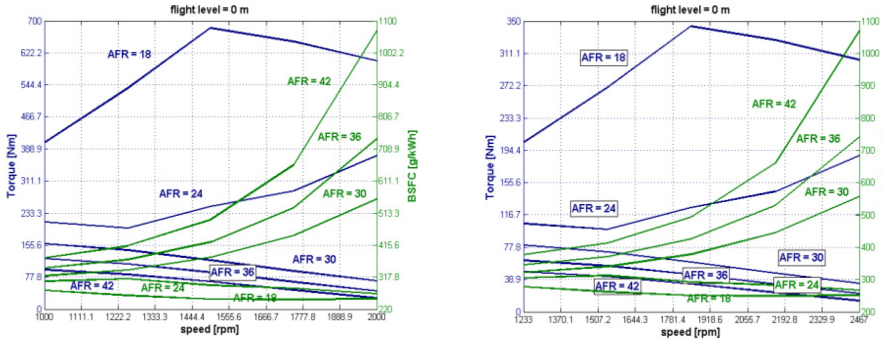
The turbocharging system has been designed to generate 128kW at 3000m. At lower altitudes, a waste-gate valve is used to control the boost pressure of the compressor as explained in the next paragraph. The turbocharger has been simulated using the full approach, which means that the software computes the dynamic balance of the turbomachines picking thermodynamic input values directly from characteristic map of both compressor and turbine. For this reason, characteristic map and momentum of inertia have to be introduced as input values.

The Uniflow system of the engine, with 14 intake ports and two exhaust valves per cylinder, has been modeled, in terms of the scavenging process, as suggested in literature [7]. The used model is based on experimental tests on 2-stroke Uniflow diesel engines and describes an intermediate behavior between the ideal models of *perfect mixing* and *perfect displacement*. Values of geometric and effective inlet and exhaust flow sections as a function of crank angle have been inputted into the code. The quality of the scavenging process has been quantified through the scavenging efficiency [7]. Other engine specifications set as input include: volume, efficiency and pressure drop of the after-cooler and geometry and lift law of the two exhaust valves. The friction power of the engine has been estimated through experiments run in motored conditions at sea level (s.l.). The Vibe model for the combustion phase has been calibrated using experimental data acquired on a similar engine prototype, operating at nominal condition, i.e. 2000 rpm and at full load (Air Fuel Ratio AFR=20). Details about the engine model and calibration can be found in [8].

3.1. Engine performance maps at sea level and in flight

A full factorial design of experiment was considered by changing the air-fuel ratio from 18 to 40 (5 levels), the engine speed from 1000 to 2000rpm (5 levels) and the altitude from 0 to 10000m (11 levels). For each of the 275 combinations, an AVL-Boost simulation has been performed. The waste-gate valve is activated at low altitude (≤3000m) to control the boost pressure of the compressor. In this way the value of the engine power can be limited to the target of 128kW. Accordingly, the pressure of the waste-gate was changed at each altitude, ranging from 2.72bar at s.l. to 3.89bar at 3000m.

The results of the Boost simulations were used to obtain the performance of the engine (Brake Specific Fuel Consumption, Power, Torque, Brake Mean Effective Pressure, Turbine Mass flow and waste-gate Mass flow) at s.l. and at each of the 11 altitudes. Fig. 2a shows the Torque/Speed/BSFC map of the 128kW engine at sea level. The efficiency map in flight at the nominal engine speed is shown in Fig. 3a.



a) b)

Fig. 2. Performance maps of reference and scaled diesel engine at sea level (s.l.); (a) 128kW engine at s.l; (b) Scaled 80kW engine at s.l.

According to the control of the waste-gate, the maximum BMEP of the engine value (see Fig. 3b) is almost constant for $0<z<3000$ and then decreases up to about 0.8MPa at 10,000m. The best fuel consumption increases from about 250g/kWh at 0m to about 280g/kWh at 7000m.

4. Downsizing of the engine

A downsizing method based on the Willans line hypothesis [7] has been implemented in PLA.N.E.S for further investigations on hybrid electric configurations. To vary the ICE size, the torque and the losses are scaled linearly with two scaling factors: displacement and stroke. This means that the reference engine and the scaled engine are assumed to have the same efficiency map in terms of Brake Mean Effective Pressure (BMEP) and piston mean speed but a different torque-speed map. To illustrate the process, the performance maps of the original 128kW engine and those of a scaled 80kW engine are shown in Fig. 2a and Fig. 2b, respectively. Note that the maps at seal level are similar but the smaller engine delivers a lower torque and rotates at a higher speed. Mass-to-power correlations will be used to obtain the expected mass of the engine for each selected size as proposed in literature[9].

In the present investigation, the nominal power of the engine has been scaled to 110 and 100kW. The displacement of the scaled engines is 2.3 and 2.0 liters and the maximum speed is 2100 and 2200 rpm, respectively.

According to results in literature [7], this scaling method is valid for scaled sizes close to the baseline size and for ICEs with fixed number of cylinders as in this case. However, the range of validity of the method for the proposed two stroke diesel engines will be analyzed as further investigation.

5. Analysis of the PLA.N.E.S. results

The simulation code PLANES has been run with the three engines (128, 110 kW and 100kW). The corresponding working points of the engines are shown in Fig. 3a. Each engine was run at its maximum speed. The power requirement for propulsion and auxiliaries along the mission was compared with the available engine power of the three engines in Fig. 1b.

The reference engine (128kW) works at its highest BMEP (and best BSFC) during takeoff and in the last part of climbing (Fig 3a). Starting from a takeoff value of about 250g/kWh, the specific fuel consumption (BSFC) increases to 300g/kWh at half of the cruise phase and reaches the highest values (800g/kWh) at descent when the engine is largely oversized. With the reference engine, the overall consumption of fuel during the mission is 204kg.

The scaled engines are able to satisfy the engine request anytime in the mission except for the take-off and a portion of climb (a) where the simulation code gives an error message. Excluding the mission portion with error messages, the downsized engines show a better fuel consumption (-6% for the 100kW engine over the entire mission) because they work in a higher efficiency zone during climb and descent. The “missing” power during take-off and climb could be obtained either by a battery-motor arrangement (hybrid electric) or a turbo-compound system. These configurations introduce a large complexity and an increase of powertrain mass and volume and will be taken into account in the next investigations.

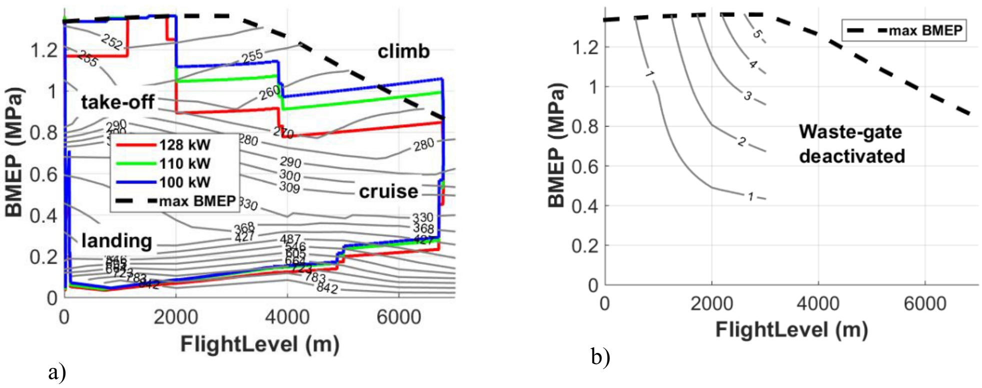


Fig. 3. Performance maps of diesel piston engines in flight (constant rpm); (a) Efficiency map of the diesel engine in flight and engine working points (contour lines showing SFC in g/kWh); (b) Map of the additional power generated by the free-turbine turbo-compound system (contour lines showing additional power in kW)

6. The turbo-compound hypothesis

A simple turbo-compound system could be obtained by adding a free turbine to recover the energy of the exhaust gases flowing through the waste-gate valve at $z \leq 3000$m. For each design of the DOE, the power that could be obtained from such free turbine has been calculated by multiplying the waste-gate flow rate by the expected enthalpy drop. The map of power obtained by the free turbine is shown in Fig. 3b. The production of power in the turbine increases with engine load and flight altitude. Unfortunately, this configuration (with the proposed control of the boost pressure) does not allow the downsizing of the engine. Not only the region of high production of power in the free turbine does not overlap with the region of lack of power but actually the energy production is zero in the working points corresponding to the climb phase where the power request is critical. However, the free turbine could be used to satisfy the electricity request of the auxiliaries. Other turbo-compound configurations will be considered as further investigation.

7. Conclusions

The simulation platform PLA.N.E.S has been used to simulate diesel piston-prop configurations of a UAV. Performance and fuel consumption maps were obtained from 1D simulation of a 128kW diesel 2stroke engine at different values of altitude and were scaled to simulate a 110kw and a 100kW engine with an appropriate downsizing procedure. The 128kW engine was found to be able to produce the power required to fly the UAV in any part of the mission with an overall fuel consumption of 204kg. Scaling the engine, the average fuel consumption was improved (up to 6%) but the climb rate of the UAV could not be sustained. The potentiality of advanced configurations like hybrid electric and turbo-compound engines to produce the missing power during climbing was addressed qualitatively and will be quantified as a future development of the investigation.

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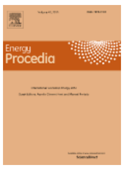

Biography

Teresa Donateo is Associate Professor of Fluid Machinery, Energy Systems and Power Generation at the University of Salento. Her research topics include simulation and optimization of piston engines and hybrid electric powertrains for land and aerial vehicles. She works in partnership with major industrial companies and the Ohio State University.